Thermal Inactivation of Airborne SARS-CoV-2 with Interior Space Heaters in Winter

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Abstract

The study aims to assess the thermal inactivation of airborne SARS-CoV-2 in a 30 m ^{3} test room by an electric heater typically used to heat interior spaces during winter, particularly in resource-limited settings. Aerosolized SARS-CoV-2 was delivered to the test room at an ambient temperature of 20 °C and 40% humidity. Two electric heaters with different power and airflow rates were operated in the test room to compare their efficiencies in the inactivation of airborne SARS-CoV-2. The first and second electric heaters had power, airflow rates, and outlet temperature of 1.5 kW, 44 m ^{3}/h, 220 °C, and 3 kW, 324 m ^{3}/h, and 150 °C, respectively. A fan drew the outside air into the heater. Air forced through the heater tunnel absorbed heat energy by interacting with the stainless steel electric tube heating elements perpendicularly located to the airflow direction, increasing outlet air temperature. The first 1.5kW electric heater was operated in the test room for 80 minutes and inactivated 99.00% of the airborne virus. The second, 3 kW electric heater was operated in the test room for 75 minutes and inactivated 99.96% of the airborne virus. The control experiment of each test experiment was conducted without turning the heaters on under otherwise identical conditions.

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ABSTRACT

The study aims to assess the thermal inactivation of airborne SARS-CoV-2 in a 30 m^3 test room by an electric heater typically used to heat interior spaces during winter, particularly in resource-limited settings. Aerosolized SARS-CoV-2 was delivered to the test room at an ambient temperature of 20 °C and 40% humidity. Two electric heaters with different power and airflow rates were operated in the test room to compare their efficiencies in the inactivation of airborne SARS-CoV-2. The first and second electric heaters had power, airflow rates, and outlet temperature of 1.5 kW, 44 m^3/h, 220 °C, and 3 kW, 324 m^3/h, and 150 °C, respectively. A fan drew the outside air into the heater. Air forced through the heater tunnel absorbed heat energy by interacting with the stainless steel electric tube heating elements perpendicularly located to the airflow direction, increasing outlet air temperature. The first 1.5kW electric heater was operated in the test room for 80 minutes and inactivated 99.00% of the airborne virus. The second, 3 kW electric heater was operated in the test room for 75 minutes and inactivated 99.96% of the airborne virus. The control experiment of each test experiment was conducted without turning the heaters on under otherwise identical conditions.

Keywords

Airborne SARS-CoV-2, Covid-19, Thermal inactivation, Electric heater, Winter, Air Pathogen Purifier

Introduction

Airborne transmission of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) is one of the main routes of pandemic spread (Bazant and Bush, 2021; Jarvis, 2020; Morawska and Milton, 2020; Tang et al., 2020; Yao et al., 2020). Airborne transmission of the virus increases in confined spaces, especially during winter. Therefore, the most effective methods to prevent pandemic spread are natural ventilation (opening windows and doors), air conditioning, and air purification devices (Morawska et al., 2020). However, natural ventilation may be unsuitable in winter due to energy costs. Currently, most purification devices use HEPA filters, UV-C, or both (Buonanno et al., 2020; Curtius et al., 2021; Darnell et al., 2004; Ma et al., 2021; Storm et al., 2020). Several studies have shown that pathogens are thermally inactivated in liquids or air (Aboud et al., 2019; Bertrand et al., 2012). Airborne pathogens' inactivation depends on air temperature. For example, Escherichia coli was inactivated at 150 @C; Bacillus subtilis was partially inactive at 150 °C, and 99.9% inactivated at 360 °C (Jung et al., 2009). Aspergillus versicolor and Cladosporium cladosporioides were inactivated by 99.00% within 0.2 seconds at 350 and 400 °C (Jung et al., 2009). MS2 virus was inactivated by 99.99% in hot air at 250°C in 2 seconds (Grinshpun et al., 2010). Another study investigated the inactivation of airborne E. coli and MS2 virus at very high temperatures and showed that both pathogens were inactivated at a rate of 4.7 $\log_{10}$ in 0.41 seconds at 450 °C (Damit et al., 2013).

SARS-CoV-2 is a single-strand RNA-enveloped virus (Ramanathan et al., 2020). It contains four structural proteins: nucleocapsid (N), spike (S), envelope (E), and membrane (M) protein. N-protein starts unfolding at 35 °C and is denatured at 55 °C (Wang et al., 2004). Heat inactivation of SARS-CoV-2 occurs through the N-Protein denaturation.

Thermal inactivation of SARS-CoV-2 in suspensions, on surfaces, or in the air has been studied and modeled for different temperatures, humidity, and exposure times (Batéjat et al., 2021; Biryukov et al., 2021; Burton

et al., 2021; Guillier et al., 2020; Seifer and Elbaum, 2021; Yap et al., 2020a). The inactivation of SARS-CoV-2 in N95 masks was investigated by exposing used N95 masks to hot air, demonstrating that SARS-CoV-2 in N95 respirators was inactivated by 99.9% at 70°C within 3 min (Yap et al., 2020b). Another study showed that SARS-CoV was ineffective in a liquid after exposure to 75°C for 45 minutes (Darnell et al., 2004). It has been shown that SARS-CoV-2 in serum became ineffective at 92°C for 15 minutes (Pastorino et al., 2020). In heat treatment of SARS-CoV-2, evaporation is a critical parameter and changes the virus inactivation half-life. Hence, the presence of the virus in a closed container or an open container affects its inactivation (Gamble et al., 2021). Heat inactivation of coronavirus has been studied in a fluidic system for different temperatures and exposure times, and complete inactivation ($>$ Log_{10} reduction) was obtained at a temperature of 83.4 °C and exposure time of 1.03 s (Jiang et al., 2021). It has been shown that SARS-CoV and SARS-COV-2 inactivation rates with temperature were the same (Hessling et al., 2020). For both viruses, a five log_{10}-reduction was obtained at temperatures of 60 °C, 80°C, and 100 °C in 32.5, 3.7, and 0.5 minutes, respectively. Both viruses were deactivated at 120°C with a five log_{10}-decline in 5.4 seconds (Hessling et al., 2020). Reduction of SARS-CoV-2 viability through solar heating in a vehicle has also been shown (Wang et al., 2021). Two studies were conducted to examine the inactivation of airborne SARS-CoV-2 as it passed through a heater (Canpolat et al., 2022; Yu et al., 2020). In one experiment, nickel foam was used as a heater, and 99.8% of the virus was inactivated at 200°C nickel foam temperature (Yu et al., 2020). In the other study, a coiled resistance wire was used as a heater, and at heater output temperatures of 150±5 °C and 220±5°C, the virus inactivation rates were 99.900% and 99.999%, respectively (Canpolat et al., 2022). However, the thermal inactivation of airborne viruses by an electric heater in a confined space has not been investigated yet.

This study used two electric heaters with different power and airflow rates to inactivate SARS-CoV-2 in a 30 m^3 test room, and their effectiveness was compared.

Materials and Methods

*2.1 Preparation of SARS-CoV-2 Suspensions*The experiments were performed in biosafety level 3 (BSL3) facilities of Antimikrop Research and Biocidal Analysis Laboratories, accredited by the Ministry of Health of Turkey. BSL3 virology laboratory is fully equipped with negative pressure vacuum systems, air-lock systems, HEPA filters, and biosafety cabinets with HEPA filters (*http://www.antimikrop.com.tr/ana-sayfa*). A stock suspension of the SARS-CoV-2 strain (Gen Bank No: MT955161.1) was used. SARS-CoV-2 virus stock was prepared by inoculating the Vero E6 cell line in Dulbecco's modified Eagle's medium with supplements (DMEM-10). Dulbecco's modified Eagle's medium containing supplements (10% fetal bovine serum, 2nM/ml L-glutamine, 100 U/ml penicillin, 100 mg/ml streptomycin, and 0.5 mg/ml fungizone (Amphotericin B)) was added to the flask, and the cells were incubated at 37°C for 72 h. When the cells were lysed >95% by the virus under the microscope, the supernatant was collected, clarified by centrifugation, and stored at -80°C. $TCID_{50}$ titer was determined by the Spearman- Kärber method as described (Hubert, 1984).

2.2 SARS-CoV-2 Test Room and the Electric Heater

Fig. 1 is the schematic representation of the 30 m^3test room where the experiments were carried out. The test room has an entry point for injection of the aerosolized SARS-CoV-2 by a venturi injector, an exit point for sample collection, an entry point for humidity regulation, air conditioning for temperature regulation, and a fan to homogenize the distribution of the aerosolized virus. A nebulizer (M102, Jiangsu Yuyue Medical Equipment & Supply Co., Ltd., Danyang Jiangsu, China) aerosolized the virus at an average nebulization rate of 0.2 mL/min at a particle size of 3.7 microns (as specified by the manufacturer).

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Fig. 1 Schematic presentation of the 30 m^3 SARS-CoV-2 test room.

A venturi injector was used to mix the aerosolized virus into the air with an airflow rate of 12 L/min via

a compressor to deliver the mixture to the test room for 20 minutes. The aerosolized virus was delivered into the 30 m^3 test room through a leakproof plastic pipeline controlled with a ball valve. In the meantime, the fan was operated to ensure airborne virus homogenization. The humidifier fixed the humidity of the test room to 40%, and the air conditioning system set the temperature of the test room to 20∓1 °C before turning the heater on.

A schematic presentation of the electric heater used in the experiments is given in Fig. 3. The electric heater consists of a fan and stainless steel electric tube heating elements. The fan draws the air inside the air tunnel. While the air passing through the heater gains heat energy by interacting with the heating elements located perpendicularly to the airflow direction, increasing the outlet air temperature of the heater within a few seconds.

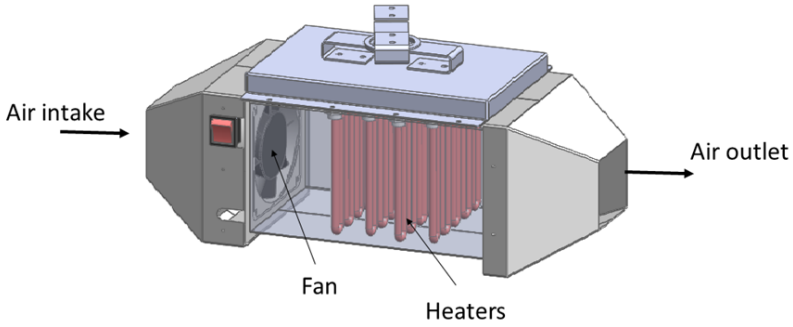
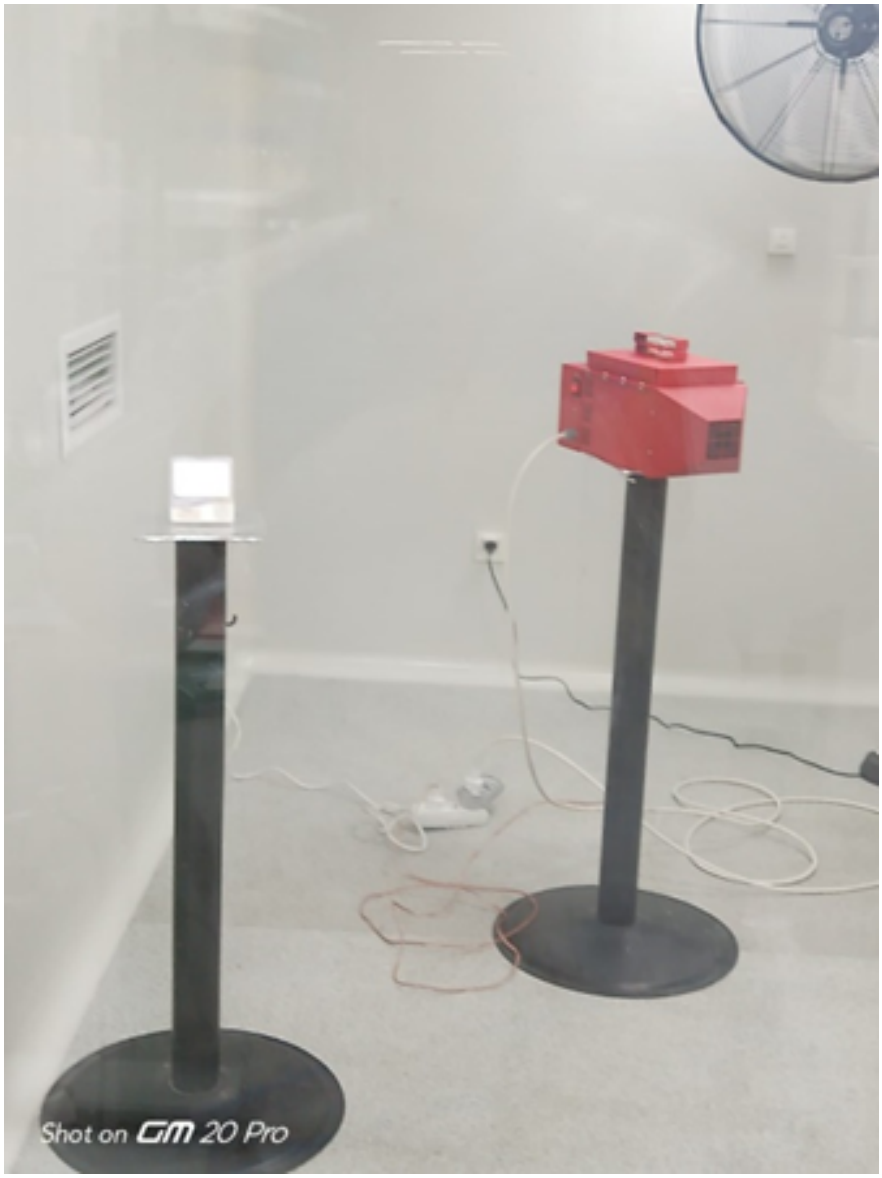


Fig. 2 Electric heater designed to inactivate airborne SARS-CoV-2 at high temperatures as air passes through it. The electric heater consists of a fan and stainless steel electric tube heating elements. The electric heater's fan draws outside air into the heater. The air heat energy increases by interacting with stainless steel electric tube heating elements perpendicularly to the airflow direction.

Two electric heaters were used to inactivate the airborne virus in the 30 m^3 test room. The small electric heater had a power of 1.5 kW, an airflow rate of 44 m^3/hour, an air travel time through the air tunnel of 0.97 seconds, and an outlet air temperature of 220 °C. The large electric heater had a power of 3 kW, an airflow rate of 324 m^3/h, an air travel time through the air tunnel of 0.03 seconds, and an outlet air temperature of 150 °C. Air travel time through the tunnel was measured as described elsewhere (Canpolat et al., 2022).

2.3 Airborne SARS-CoV-2 Inactivation Experiments

In the first experiment, one of the electric heaters was located one meter above the floor, as seen Fig 3(a). The other electric heater was situated on the floor in the second experiment, as shown in Fig. 3(b). The first electric heater has smaller power and airflow capacity than the second one. Therefore, the first electric heater will be named as "small electric heater" and the second one a "large electric heater" from here on.



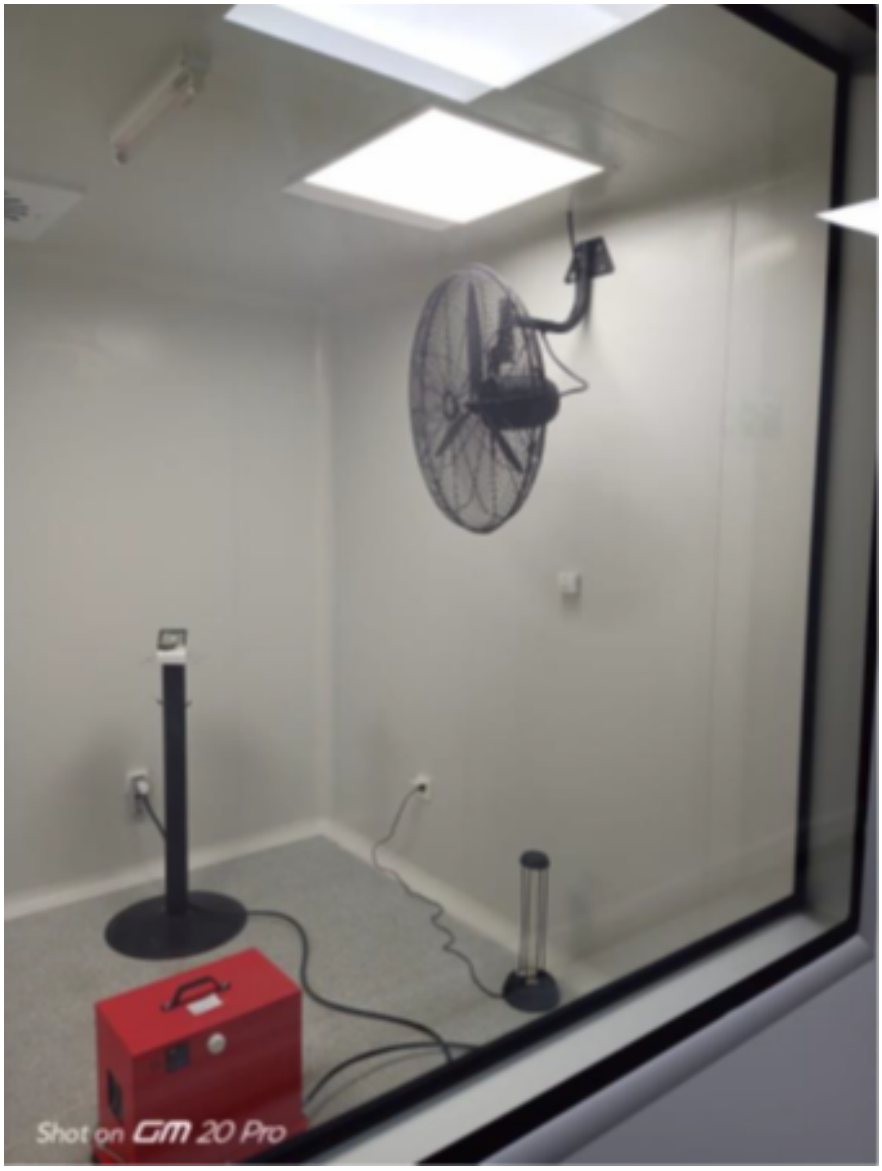


Fig. 3. (a) The first electric heater at one meter high in the test room operated for 80 minutes. (b) The second electric heater on the ground operated for 75 minutes.

During the set-up of the experimental procedure, six control experiments were carried out to determine the $TCID_{50}$ titer of SARS-CoV-2 in the remaining stock solution after the nebulization process. The mean $\log_{10}$ $TCID_{50}$ titer of the virus stock solution was 7.50 ± 0.30. At the beginning of the experiments, the test room's temperature was 20 ∓ 1°C, at 40% humidity. At the end of all experiments, one m^3 of air was drawn from the test room through a hose connected to a vacuum pump (MD8 Airscan, Sartorius, Göttingen, Germany). The inlet gelatin membrane filter (Sartorius, Göttingen, Germany) on the hose collected airborne virus while the vacuum pump drew air from the test room. Next, the filter was dissolved in phosphate-buffered saline (PBS) at 37 °C, and the $TCID_{50}$ titer of the solution was determined by the Spearman- Kärber method as described (31). Briefly, Log_{10} dilutions of the harvest from the filter (10^{-1} to 10^{-6} dilutions) were transferred to 96-well plates containing Vero E6 cells and incubated at 37 ∓ 1 °C, 5% CO2 conditions. After four days of incubation, the cytopathic effect was evaluated under an inverted microscope, and the virus $TCID_{50}$ values

of the gelatin filter were obtained in control and the test experiments.

In the first experiment, the small electric heater was operated in the test room for 80 min after the nebulization. The control experiment was performed under the same conditions, except the electric heater was off. In the second experiment, the large electric heater was operated in the test room for 75 min, and the control experiment was performed while the electric heater was off. Due to the temperature increase in the test room, the large electric heater was 5 min less operated than the small electric heater.

Results and Discussion

After running the small electric heater in the test room for 80 minutes, the airborne SARS-CoV-2 $\log_{10}$ $TCID_{50}$value was $\log_{10}$T=2.63. After the control experiment, the $\log_{10}$ $TCID_{50}$ value was $\log_{10}$C=5.00. Total $\log_{10}$- reduction in the infectivity of airborne SARS-CoV-2 in the test room was,$LR_{S,total}$ = $\log_{10}$C-$\log_{10}$T= 2.37 (99.57%). At the end of the experiment, the room temperature was 40∓1°C at a relative humidity of 23%. Subindexes $S$and L refer to small and large electric heaters.

The $\log_{10}$ $TCID_{50}$ value of the airborne SARS-CoV-2 in the test room after running the large electric heater for 75 min was $\log_{10}$T=0.75, and for the control experiment, it was $\log_{10}$C=4.88. For the large electric heater,$LR_{L,total}$ =4.13 (99.99%). After the test experiment, the room's temperature was 47∓1 °C at a relative humidity of 19%.

The inactivation of airborne SARS-CoV-2 as a function of airflow temperature has been previously studied (Canpolat et al., 2022; Yu et al., 2020). The present study investigated the thermal inactivation of airborne SARS-CoV-2 in a 30 m^3 test room. In this study, the small electric heater had an airflow rate of 44 m^3/h and an air outlet temperature of 220°C. It was operated for 80 min in the test room, and 58.6 m^3 of air passed through the heater. As a result, the total circulating air through the heater was 1.95 times the volume of the test room, and 99.57% of the airborne SARS-CoV-2 lost infectivity. The large electric heater had an airflow rate of 324 m^3/h and an air outlet temperature of 150°C, and it was operated for 75 min in the test room. In this experiment, the total circulating air through the large electric heater was 13.5 times the volume of the test room, and the airborne SARS-CoV-2 was inactivated by 99.99%.

At the end of the experiments with the small and large electric heater, the test room temperature was 40 °C, at 23% humidity, and 47 °C, at 19% humidity, respectively. Increased air temperature in the test room also reduces the infectivity of the viruses. The viruses may lose their infectivity either during passing through the electric heater or due to the increased room temperature. Therefore, we defined the total logarithmic reduction (LR_{total}) as a sum of reductions in viability due to the electric heater and an increase in the room's air temperature. In order to achieve the heater's effectiveness in reducing the viability of viruses (LR_{EH}), the contribution of room temperature in reducing the viability of viruses (LR_{RT}) should be subtracted from theLR_{total} . The room temperature and time dependence of the LR_{RT} in the infectivity of SASR-CoV-2 can be expressed as (Hessling et al., 2020)

$$\mathrm{LR_{RT}} = k\,(T)\,.t = 10^{-\frac{5574.7}{T}+15.928}.\mathrm{t} \qquad (1)$$

Where *k(T)* is the inactivation rate constant of SARS-CoV-2 in the first-order reaction model, T is the temperature in degrees Kelvin, and t is the time the virus was exposed to heat at the temperature of T . In the use of the small electric heater, the test room temperature increased from 293 °K (20°C) to 313 °K (40°C) in 80 minutes, and in the use of the large electric heater, the temperature increased from 293 °K to 320 °K (47 °C) in 75 minutes. We did not record the time-dependent temperature variation in the test room during the experiments; therefore, we can not directly calculate the temperature-dependent LR_{RT} value using Eq.1. Here, we assumed that the temperature increases linearly with time and calculated the temperature rise per minute for both electric heaters to obtain LR_{RT}. The temperature increase per minute for the small and large electric heaters are ΔT =0.25°K and ΔT = 0.36 °K, respectively. In that case, Eq.1 can be written in a discrete form as

$$\mathrm{LR_{RT}} = \sum_{i=0}^{t} 10^{-\frac{5574.7}{293+i*T}+15.928} \qquad (2)$$

The temperature increased by ΔT in each time interval of$i$ = 0, 1, 2, ..., t . Here, each time interval is one minute. For the small and the large electric heater experiments, the time t is 80 and 75, respectively, in Eq. 2. TheLR_{RT} was calculated for the small and large electric heater using Eq. 2 and obtained as$LR_{S,RT}$ = 0.37, and $LR_{L,RT}$=0.68, respectively. The $LR_{S,total}$ =2.37 (99.57% decrease in infectivity), which is much higher than the$LR_{S,RT}$ =0.37 (57.14% decrease in infectivity). The small electric heater's net contribution in the logarithmic reduction was $LR_{S,EH}$ =$LR_{S,total}$ - $LR_{S,RT}$ = 2.00 (99.00%). For the large electric heater,$LR_{L,total}$ =4.13 (99.99%) and$LR_{L,RT}$ = 0.68 (79.15%), and the net contribution of the large electric heater was, $LR_{L,EH}$ = 3.45 (99.96%). Potentially, viral loss also occurs during nebulization and air removal from the test room. However, since both processes were carried out under the same conditions in the control and test experiments, these losses have no effect when calculating the viral loss from the electric heater.

In addition to the air outlet temperature, the number of recirculations of all the air in the room within a given time may be an essential factor for the inactivation of airborne SARS-CoV-2 in the test room. In our first study (30), it was shown that the infectivity of the virus in the air passed through the electric heater decreased by 99.900% and 99.999%, at the electric heater's outlet air temperatures of 150°C and 220 °C, respectively. Hence, we may define the $\log_{10}$ reduction of the infectivity (LR_T) as a function of the outlet air temperature of the electric heater and writeLR_{150} =3, and LR_{220} =5 and percentage reduction as PR_{150} =99.900% andPR_{220} =99.999%. In a room of volumeV_r , if all the room air passes through the electric heater, the logarithmic reduction in airborne virus infectivity in the room should be equal to the LR_T value. If all the air in the room passes through the electric heater $n$times, the logarithmic reduction in the airborne coronavirus infectivity ($LR_{n,T}$) and the percentage reduction ($PR_{n,T}$) for the room can be defined as

$$\mathrm{LR}_{n,T} = n.\mathrm{LR}_T \tag{3}$$

and

$$\mathrm{PR}_{n,T} = \left(1 - 10^{-\mathrm{LR}_{n,T}}\right).100\% \tag{4}$$

$$n = \frac{\mathrm{t}.\Phi}{V_r}$$

The n depends on the operating time of the heater (t), the electric heater's air flow rate (Φ), and the room volume,V_r=*30 m^3* . The small electric heater with the outlet air temperature of T =220°C, RL_T =5, t =80 min,Φ = 44 m^3/h, n =1.95, and $LR_{S,n,T}$ =9.75. The measured logarithmic reduction is due to the small electric heater, $LR_{S,EH}$ =2.00, and the ratio of$LR_{S,n,T}$ /$LR_{S,EH}$ = 4.87. For the large electric heater with the outlet air temperature of$T$ =150 °C,$LR_{L,T}$ = 3, t = 75 min,Φ = 324 m^3/h, n =13.88 and$LR_{L,n,T}$ = 41.64. The measured logarithmic reduction after the experiment using the large electric heater is$LR_{L,EH}$ =3.45, and the ratio of$LR_{L,n,T}$ /$LR_{L,EH}$ =12.07.

If all air in the room had passed through the electric heaters $n$times, the ratio $LR_{n,T}/LR_{EH}$ would equal one. The ratio is 4.87 for the small electric heater and 12.07 for the large electric heater. Let's assume that for everyV_r m^3 of air that passes through the device, x fraction of it is the air that passes more than once, and *1-x* fraction of the room's air volume passes through the heater once. In that case, we can re-write Eq. (3) and Eq. (4) as

$$\mathrm{LR}_{n,T,x} = (1-x).\mathrm{n}.\mathrm{LR}_T \tag{5}$$

$$\mathrm{PR}_{n,T,x} = \left(1 - 10^{-\mathrm{LR}_{n,EHx}}\right).100\% \tag{6}$$

Where $LR_{n,T,x}$= $LR_{L,EH}$ for the small electric heater and $LR_{n,T,x}$= $LR_{S,EH}$ for the large electric heater. During each circulation of the air volume of V_r through the electric heater, xV_r m^3 of the air volume a second time passes through the electric heater, and the same amount of the air volume does not pass through the heater. We did not count the LR of the air that second time passed through the heater in the circulation of the air volume of $V_r$in Eq. (5) and Eq. (6). We can calculate the x value using Eq. (5) as

$$1 - x = \frac{\mathrm{LR}_{n,T,x}}{\mathrm{n.LR}_T} \quad (7)$$

For the small electric heater $LR_{n,T,x}$ =2.0, LR_T =5, n =1.95, and x =0.80. For the large electric heater, $LR_{n,T,x}$ =3.45, LR_T =3, n =41.64, and x =0.97. These results show that, for the small electric heater, for each circulation of the air volume of V_r, *0.8*V_r of the air volume passes through the heater a second time, and *0.2*V_r volume of the air passes the first time through the electric heater. Here we can call the coefficient *1-x* in Eq. (5) the "air circulation efficiency" of the electric heater, and its value is 0.2 for the small electric heater and 0.03 for the large electric heater. This means that for the circulation of all the air in the room, the volume of air that must pass through the device is *V =Vr/(1-x)* . The air volume is *V=5Vr for* the small electric heater and *V= 33.3Vr* for the large electric heater. The small electric heater is more efficient than the large one at circulating all the air in the room.

For the small electric heater, n =1.95 and *1/(1-x)* =5, and since *n<1/(1-x*), it means that all the air in the room did not pass through the electric heater, and the expectation is $LR_{S,EH}<LR_T$. The results are consistent with the estimation since $LR_{S,EH}$ = 2.0, and LR_T =5. The fact that n =41.64 and *1/(1-x)* = 33.3 and *n>1/(1-x)* for the large electric heater indicates that all the air in the room passed through the electric heater, and must be $LR_{L,EH}>LR_T$. Therefore, the measured $LR_{L,EH}$ =3.45, and LR_T =3 are consistent with the expected result.

Two electric heaters with powers of 1.5 kW and 3 kW and an airflow rate of 44 m^3/h and 324 m^3/h were used in the SARS-CoV-2 test experiments in a 30 m^3 room, leading to the room temperature increase of 20 °C and 27 °C while simultaneously reducing the infectivity of airborne SARS-CoV-2.

The x value is smaller for the small electric heater than the large electric heater, indicating that the small electric heater is better at circulating all air room than the large electric heater. Hence, having more small electric heaters, such as 3-4, locating different corners of the room may be more effective in reducing the infectivity of the airborne SARS-CoV-2.

The developed electric heater has the potential to be used to heat interior spaces while also reducing the infectivity of SARS-CoV-2 in homes, shopping centers, restaurants, classrooms, rooms in hospitals, offices, and public transport vehicles such as trains, metro, and tramways during winter. We propose a method to evaluate the efficacy of two electric heaters in reducing the infectiousness of airborne SARS-CoV-2 in a test room. As a result, we defined the *1-x* parameter named "air circulation efficiency" to measure the efficiency of an electric heater at circulating air in the room. The air circulating efficiency parameter may depend on the volume of the room, the airflow rate, the device inactivation rate, the number of devices in the room, and their locations. Therefore, more experiments should be performed for the optimization of reducing the infectivity of airborne viruses in a confined space. Furthermore, this *1-x* parameter can be used for air purification devices such as UV-C and HEPA filters.

There are some limitations of the study, such as a lack of monitoring temperature of the test room and repetition of the test experiments due to limited sources. One other limitation is the air extraction from only one location in the test room to measure the airborne virus infectivity.

Conclusion

The developed electric heater uses the same energy to heat an enclosed space and reduce the viability of airborne SARS-CoV-2. It has the potential to inactivate SARS-CoV-2 and other airborne pathogens during the winter months. Therefore, further experiments with different viruses and bacteria are needed. Nevertheless, the electric heater can potentially prevent the airborne spread of the pandemic indoors, besides heating in winter. The dual function of the electric heater gives it an edge over air purifiers such as UV-C or HEPA filters for winter use.

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Author Contributions

Conceptualization, MC, and CS; Methodology, MC and CS; Formal Analysis, MC and CS ; Investigation, MC, AYC, SB, DK, CS, and ET; Data Curation, MC and CS; Writing – Original Draft Preparation, MC, CS; Writing – Review and Editing, ACY and ET.

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